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TECHNICAL REPORT ARLCB-TR-~~79007~~

THE EQUIVALENCE OF K_{Ic} AND J_{Ic} FRACTURE-TOUGHNESS MEASUREMENTS IN NI-CR-MO STEELS

John H. Underwood

May 1979

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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BENÉT WEAPONS LABORATORY
WATERVLIET, N. Y. 12189

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TECHNICAL REPORT

THE EQUIVALENCE OF K_{Ic} AND J_{Ic} FRACTURE-TOUGHNESS MEASUREMENTS IN NI-CR-MO STEELS

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Several series of fracture-toughness measurements were made in 4340 type steels, using both the standard K_{Ic} test method and the J_{Ic} test method described by Landes and Begley. K_{Ic} results and J_{Ic} results converted to K_{Ic} units are nearly identical for a given steel over a range of specimen size. The fracture toughness of steels produced by vacuum-degassing, remelt, and airmelt processes are compared over a range of yield stress. Simplified J_{Ic}

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test procedures are suggested for use with Ni-Cr-Mo steels within certain ranges of yield stress and specimen geometry.

The Equivalence of K_{Ic} and J_{Ic} Fracture-toughness Measurements in Ni-Cr-Mo Steels

K_{Ic} and J_{Ic} tests show similar results for a range of yield stress

by John H. Underwood

ABSTRACT—Several series of fracture-toughness measurements were made in 4340 type steels, using both the standard K_{Ic} test method and the J_{Ic} test method described by Landes and Begley. K_{Ic} results and J_{Ic} results converted to K_{Ic} units are nearly identical for a given steel over a range of specimen size. The fracture toughness of steels produced by vacuum-degassing, remelt, and airmelt processes are compared over a range of yield stress. Simplified J_{Ic} test procedures are suggested for use with Ni-Cr-Mo steels within certain ranges of yield stress and specimen geometry.

Introduction

The test method for measuring plane-strain fracture toughness, K_{Ic}, of structural alloys has been standardized by ASTM[1] and is well accepted. The requirement in the test method which most often limits its use for measuring K_{Ic} is the specimen-size requirement, which is that the crack length, a, and the specimen thickness, B, must be greater than the quantity $2.5[K_{Ic}/\sigma_{YS}]^2$. The J_{Ic} test method currently being developed[2] shows promise of becoming a generally useful method for measuring fracture toughness with considerably less limitation on specimen size. The basic reason for this is that the J_{Ic} method is not limited to the linear-elastic range of material behavior.

In order for the J_{Ic} test to become a well-accepted method for measuring fracture toughness it must be demonstrated that the value of J_{Ic} measured from a given alloy and mechanical condition is invariant over a range of specimen size. In addition, it would be desirable to demonstrate that the values of J_{Ic} measured over a range of mechanical conditions of various alloys have a fixed relationship to values of K_{Ic} measured using the standard method. The main objectives of this work are to show the invariance of J_{Ic} with specimen size and the relationship between J_{Ic} and K_{Ic} for one type of Ni-Cr-Mo steel in various heat-treat conditions. Additional objectives are to describe the fracture toughness of the Ni-Cr-Mo steel as a function of yield stress, using K_{Ic}, J_{Ic}, and Charpy-energy measures of fracture toughness, and to describe a simplified J_{Ic} test procedure which can be used for the Ni-Cr-Mo steel within certain ranges of yield stress and specimen geometry.

Test Procedures

Material

The fracture-toughness measurements described in this work are from Ni-Cr-Mo steels produced using three different types of processes. The main concern is with steel forgings from which large-caliber cannons are manufactured. Cannon forgings are produced by several steel manufacturers using electric-arc-furnace and vacuum-degassing procedures. The forging is performed using the conventional open-die process. The size of the forgings is typically in the range 0.3 to 0.4 m in diameter and 5 to 10 m in length. The forgings are austenitized, quenched and tempered to a yield stress in the range 1000 to 1200 MN/m^2. The chemical composition, yield stress and fracture toughness are shown in Table 1 for two cannon forgings from which much of the results were obtained. The range of these same properties is shown for all of the cannon forgings discussed in this work.

Fracture-toughness measurements were also made from steels produced using two remelting processes for comparison with measurements from cannon forgings. Measurements were made from a vacuum-arc-remelt, forged steel and an electro-slag-remelt steel, both as-cast and forged. The composition and mechanical properties of these steels are shown in Table 1.

Fracture toughness values were obtained from the published literature[3,4] for conventional, AISI 4340, air-melt steel. The standard range of composition of 4340 steel is shown in Table 1, along with the range of mechanical properties which are compared with the results in this work.

Test Arrangements

The two types of specimen and the test arrangement which were used are shown in Fig. 1. The compact specimens were either the standard specimen geometry[1] or the slight modifications to the standard geometry shown in Fig. 1. The modifications consisted of the clip-gage displacement being measured along the load line of the specimen and a slightly larger loading-hole spacing to accommodate the load-line measurements. Neither

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TABLE 1—MATERIAL PROPERTIES

	Ni	Cr	Mo	Mn	C	Composition Weight, % Si	V	S	0.1% Yield Stress MN/m²	Fracture Toughness MN/m³/²
Cannon Forgings										
Compact Comparison Specimens	3.02	0.92	0.61	0.38	0.35	0.21	0.11	0.010	1280	130
C-Shaped Comparison Specimens	3.08	1.15	0.58	0.50	0.34	0.22	0.13	0.011	1230	142
Range of all Specimens	2.38—3.26	0.84—1.15	0.45—0.65	0.38—0.60	0.31—0.37	0.02—0.22	0.08—0.13	0.007—0.011	1100-1350	120-200
Remelt Processes										
VAR; forged	1.97	0.99	0.48	0.86	0.30	0.31	0.08	—	900-1200	160-280
ESR; as-cast, forged	2.25	1.05	0.48	0.49	0.33	0.17	0.10	0.010	850-1200	140-260
4340 Air Melt	1.6—2.0	0.7—0.9	0.2—0.3	0.6—0.8	0.38—0.43	.20—.35	— —	0.04 max	1000-1400	70-140

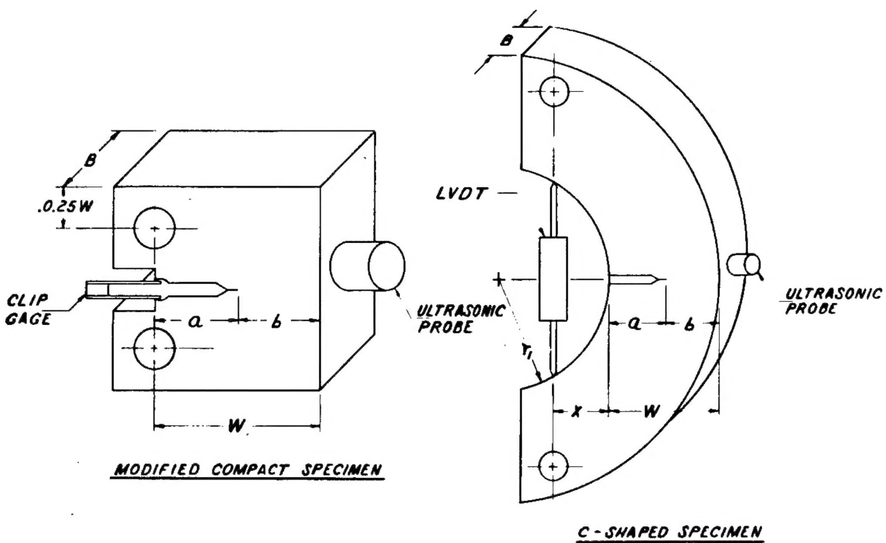

Fig. 1—Test arrangements

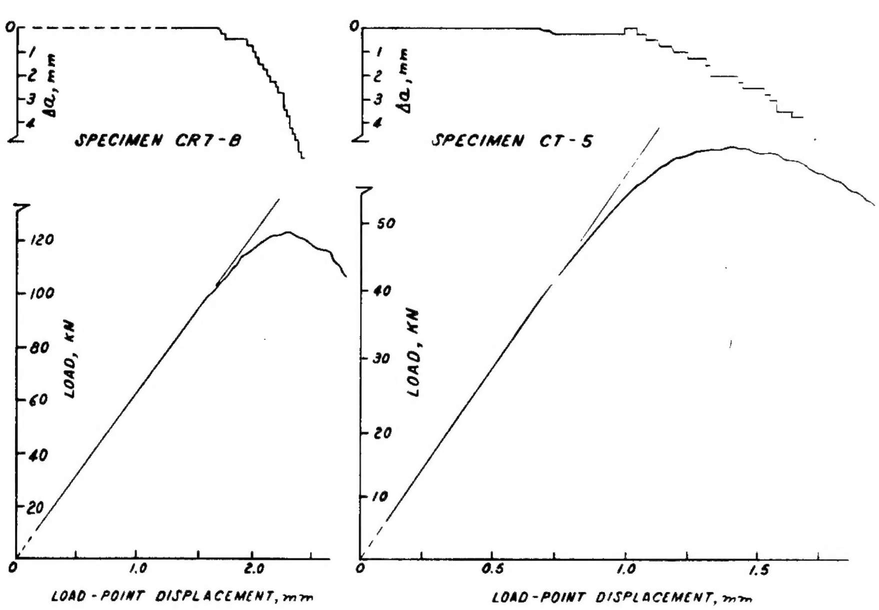

Fig. 2—Load vs. load-point displacement and crack growth vs. load-point displacement

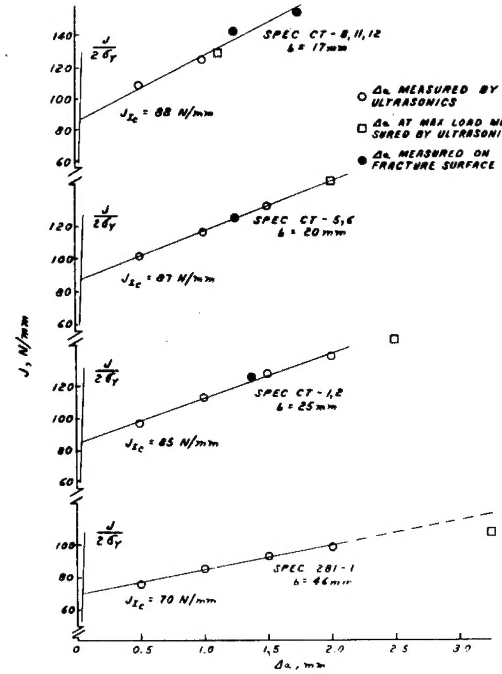

Fig. 3—*J* vs. crack-growth plots for compact specimens

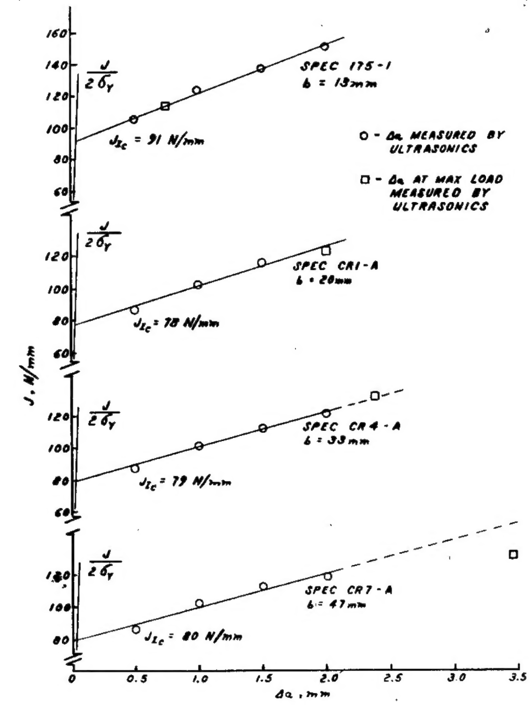

Fig. 4—*J* vs. crack-growth plots for C-shaped specimens

modification had any significant effect on the K_{Ic} measurements, and the modifications facilitated J_{Ic} measurements which require that the specimen displacement be along the load line.

The C-shaped specimens were the same basic geometry as that described in recent work[5] and which will be included in the next revision of the ASTM K_{Ic} test method.[1] The displacement was measured along the load line using a linear-variable-differential transformer as shown in Fig. 1, so that the measurements could be used for J_{Ic} as well as K_{Ic} determination.

For both types of specimen, the end-on, ultrasonic method[6] was used to measure crack growth during the fracture-toughness tests. As can be seen in Fig. 1 the end-on method uses an ultrasonic probe placed directly ahead of the crack, rather than normal to the crack plane as is more usual. This requires relatively high-gain ultrasonic equipment and relatively clean material, so that the ultrasonic signal reflected from the crack tip can be detected with a minimum of interference from inclusions in the material. End-on crack measurement is made quite routinely in the vacuum-degassed steel described here using commercially available ultrasonic equipment. The only specialized equipment used is the digital crack-depth

TABLE 2—TEST DATA FOR COMPARISON SPECIMENS

Compact Specimens				C-Shaped Specimens					
Spec. No.	W, mm	B, mm	Measurement of Δa	Spec. No.	W, mm	b, mm	B, mm	X, mm	r_1, mm
1B1-2	102	47.0	ultrasonics	CR7-A	95.2	47.2	50.8	71.4	95.2
1B1-4	102	47.0	ultrasonics	CR7-B	95.2	46.0	50.8	71.4	95.2
2B1-1	102	46.0	ultrasonics						
2B1-4	102	46.0	ultrasonics	CR4-A	66.3	32.8	50.8	49.7	66.3
				CR4-B	66.3	32.0	50.8	49.7	66.3
CT-1	50.8	24.7	ultrasonics						
-2	50.8	24.3	surface	CR1-A	39.9	20.1	50.8	29.9	39.9
-3	50.8	22.3	ultrasonics	CR1-B	39.9	19.1	50.8	29.9	39.9
-4	50.8	22.1	surface						
-5	50.8	20.0	ultrasonics	175-1	34.0	12.7	25.4	35.6	51.0
-6	50.8	19.9	surface	175-3	34.0	12.9	25.4	35.6	51.0
-8	50.8	17.5	ultrasonics						
-11	50.8	17.0	surface						
-12	50.8	16.9	surface						

Specimen CR4-B

Specimen CT-2

Fig. 5—Fracture surfaces

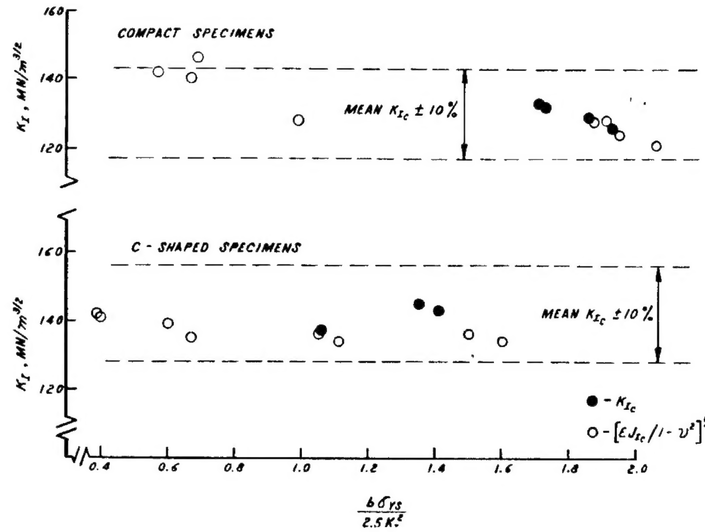

Fig. 6—K_{Ic} and $[EJ_{Ic}/1 - \nu^2]^{1/2}$ for various specimen sizes

reader[6] which converts the output of the ultrasonic equipment into a signal which is plotted simultaneously with the load vs. displacement record (see Fig. 2).

J_{Ic} Test Method

A continuous plot of crack growth, Δa, during the fracture-toughness test provides the information required to calculate J_{Ic} from a single test. The procedure followed here, essentially as suggested by Landes and Begley[2] except for the measurement of crack growth, is the following. Referring to Fig. 2, the area under the load vs. load-point-displacement curve is measured at points corresponding to 0.5, 1.0, 1.5 and 2.0 mm of crack growth determined by ultrasonics. The values of J are calculated for these points using the relation

$$J = 2A/bB \tag{1}$$

where A is the area under the load vs. load-point-displacement curve, b is the uncracked ligament, B is the specimen thickness. A plot of J vs. Δa is made for each test (see Figs. 3 and 4). A straight-line representation of the data is made using standard linear-regression procedures. The J_{Ic} value is then the intersection of the linear regression line with the so-called blunting line which is defined as $J = 2\sigma_y \Delta a$, where σ_y is the flow stress of the material, that is, the average of the yield and the ultimate tensile stress. The procedure for determining J_{Ic} gives in effect the critical J value at which the first actual crack growth begins over and above the apparent crack growth associated with plastic blunting and stretching at the crack tip.

Discussion of Results

K_{Ic} - J_{Ic} Comparison Tests

Two groups of specimens were tested so that K_{Ic} and J_{Ic} results over a range of specimen size could be compared. A group of compact specimens was taken from the forging with the first listed properties in Table 1; a group of C-shaped specimens was taken from the forging listed second in the table. All specimens were in the C-R orientation[1] as indicated in Fig. 1. The test data for both groups are shown in Table 2. Note that the uncracked ligament, b, varies as well as the overall size, W. For all the specimens, the smallest dimension in the crack-tip area was the uncracked ligament, so this is the dimension of interest when a comparison of K_{Ic} and J_{Ic} results is made.

Figures 3 and 4 show the J vs. Δa plots for the compact and C-shaped specimens, respectively. In general, the straight line which determines the value of J_{Ic} for each plot was calculated by linear regression of four data points obtained from ultrasonic measurements. For the plot of CT-8 in Fig. 3, data obtained from the fracture surfaces of specimens CT-11 and 12 were also used because of the small range of ultrasonic data in this case. Figure 5 shows one fracture surface from each of the specimen groups. The dark band on the fracture surface of specimen CT-2 is the crack growth which occurred during the J_{Ic} test up to the point of unloading of the specimen. The light areas of fatigue precrack and additional fatigue cracking after unloading clearly outline the crack growth which occurred during the J_{Ic} test. Specimens CT-2, 6, 11 and 12 were unloaded and fatigue postcracked in this manner. For these four specimens, the data points (in Fig. 3) with Δa obtained from the fracture surface are closely in line with the data from ultrasonic measurements.

The result considered most important in Figs. 3 and 4 is the relatively constant value of J_{Ic} obtained from each group of tests, particularly considering that the remaining ligament varies by about a factor of 3 in each group. For the compact specimen results, the J_{Ic} value from the specimen with the largest b varies the most from the other results; for the C-shaped results the J_{Ic} value from the specimen with the smallest b varies the most. Since these variations follow no size trend, they are attributed to experimental scatter.

A further point regarding the data in Figs. 3 and 4 concerns the maximum load point in the J_{Ic} tests. There is a consistent trend in all the data toward a smaller amount of crack growth at the maximum load point as the remaining ligament becomes smaller. This trend has been observed in different materials by others. It can be useful for establishing a simplified J_{Ic} test procedure, as discussed in a forthcoming section.

A direct comparison of the fracture toughness measured using the standard K_{Ic} method with the fracture toughness measured using the J_{Ic} method is shown in Fig. 6. The J_{Ic} values are those obtained from the eight compact specimens and the eight C-shaped specimens listed in Table 2 for which ultrasonic measurements were obtained. The parameter $[EJ_{Ic}/1 - \nu^2]^{1/2}$, often used to convert J_{Ic} values to K_{Ic} units, is plotted vs. the ratio of ligament size to required specimen size. For some of the specimens, valid K_{Ic} values could also be obtained, as shown in Fig. 6. With one exception the values of $[EJ_{Ic}/1 - \nu^2]^{1/2}$ are within 10 percent of the mean K_{Ic} value, and there is no significant trend away from the mean K_{Ic} as the uncracked ligament decreases in size. This is considered the most direct indication of the general equivalency of the K_{Ic} and J_{Ic} procedures for measuring fracture toughness of the material considered here.

For the final comments regarding the comparison of K_{Ic} and J_{Ic} values, refer to Table 3. Shown here are the K_{Ic} values referred to in the foregoing paragraph and the corresponding values of $[EJ_{Ic}/1 - \nu^2]^{1/2}$. Also shown are values from another parameter which has proven useful for this material, $[EJ/1 - \nu^2]^{1/2}_{\Delta a = 0.5\ mm}$. This parameter is calculated simply by using the J value at an ultrasonically measured crack growth of 0.5 mm. For the data in Table 3, the value of $[EJ_{Ic}/1 - \nu^2]^{1/2}$ averages 4.5 percent below K_{Ic}, and the value of $[EJ/1 - \nu^2]^{1/2}_{\Delta a = 0.5\ mm}$ averages within 1 percent of K_{Ic}. For the material considered in this work, it has been found in general that J_{Ic}, when converted to K_{Ic} units, is about 5 percent lower than K_{Ic}, and that the J value at 0.5-mm crack growth, when converted to K_{Ic} units, is approximately equal to K_{Ic}.

TABLE 3—COMPARISON OF THREE MEASURES OF FRACTURE TOUGHNESS

Spec. No.	K_{Ic}, MN/m$^{3/2}$	$[EJ/(1 - \nu^2)]^{1/2}_{\Delta a = 0.5\ mm}$ MN/m$^{3/2}$	$[EJ_{Ic}/(1 - \nu^2)]^{1/2}$ MN/m$^{3/2}$
1B1-2	129	134	127
1B1-4	133	131	128
2B1-1	126	132	124
2B1-4	132	128	121
CR7-A	143	142	134
CR7-B	145	144	136
CR4-A	137	142	134

Fracture Toughness vs. Yield Stress

Fracture-toughness tests have been performed from a large number of cannon forgings in recent years. Although some of these tests were with nontypical materials or nonstandard procedures, the rest provide quite sufficient data to describe the fracture toughness of the Ni-Cr-Mo steel used for cannon. Figure 7 is a summary of these data. Four groups of tests were from production cannon forgings; four groups, *e* through *h*, were from forgings which were equivalent to production forgings but used for R & D purposes. The size of the forgings is indicated by the inner radii, r_1, shown in Fig. 7, which are about one half of the outer radii. See Table 1 for the range of material properties of the cannon forgings discussed here. The yield stress and Charpy tests were performed in general by the forging manufacturers; some of these values were rechecked in this laboratory, and no significant differences were noted. The fracture-toughness tests were all performed in this laboratory in the C-R orientation using the K_{Ic} and J_{Ic} procedures already described. The one procedure not yet discussed is the use of the K_{Ic} method with specimens somewhat smaller than that required by the ASTM method. Since the specimen size was never less than one half of the requirement and all other requirements of the method were met, including the requirement that the ratio of maximum load to 5-percent offset load be less than 1.10, the results from the undersized specimens are considered to be good estimates of K_{Ic}.

The data in Fig. 7 give a reliable description of the fracture toughness vs. yield stress of cannon forgings. This is indicated by a correlation coefficient of -0.97 for the linear-regression line. Another indication is the fact that only one data point falls outside the ± 15 NM/m$^{3/2}$ scatter band. Considering that the data were taken from 17 forgings supplied by two manufacturers, the scatter is very small.

The relative scatter in the Charpy data is much larger, as is expected. Still, the Charpy data clearly show a decreasing toughness with increasing yield stress. The decrease in Charpy energy appears not to be linear with increasing yield stress, as opposed to the linear or nearly linear decrease in fracture toughness with increasing yield stress. Also, note that, while fracture toughness changes by less than a factor of 2 over range of yield stress investigated, Charpy energy changes by more than a factor of 3. So, although Charpy energy follows the same general trend as fracture toughness, a direct linear correlation between the two apparently does not exist for this material.

A comparison of the fracture toughness of the Ni-Cr-Mo steel used in cannon with that from three similar steels with different processing is shown in Fig. 8. The fracture

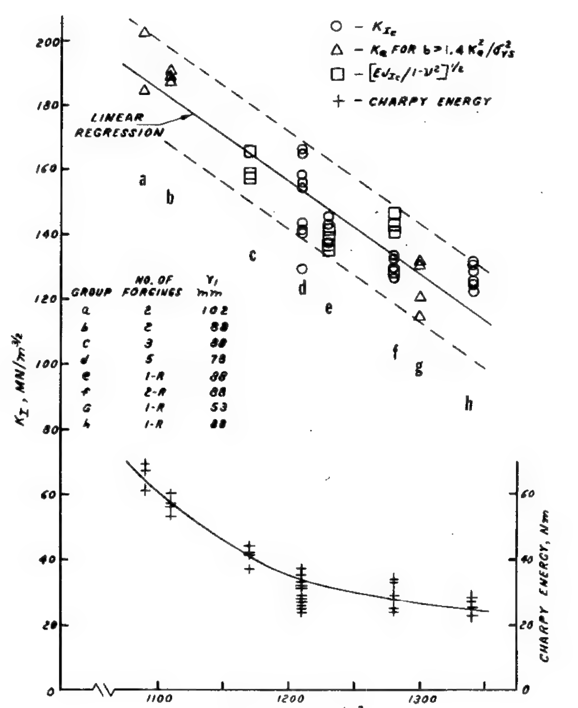

Fig. 7—Fracture toughness and Charpy energy vs. yield stress for cannon forgings

toughness of the VAR and ESR material is presented as the parameter $[EJ/1 - \nu^2]^{1/2}_{\Delta a=0.5\ mm}$, described in relation to Table 3. There is certainly no large difference between the fracture toughness of these remelt-process steels and the vacuum-degassed cannon steel; for the tests in which the yield-strength ranges overlap, there is no significant difference in fracture toughness, and outside the area of overlap nothing in the tests indicated any difference. There is an obvious difference between the fracture toughness of airmelt 4340 steel and that of the cannon and remelt steels, and the difference becomes more pronounced at low values of yield stress. The comparison shown is between the C-R orientation for the cannon and remelt steels and the L-T orientation for the 4340 steel. So, regardless of a more favorable orientation with the 4340 steel, the higher toughness of the cannon and remelt steels is still apparent.

Simplified J_{IC} Test

Based on the tests here, two simplified J_{Ic} test procedures can be suggested for use with Ni-Cr-Mo steels. The first is the use of the J value at 0.5 mm of crack growth, as used here in the tests described in Table 3 and Fig. 8. The experience of this laboratory is that this procedure gives a good estimate of fracture toughness for Ni-Cr-Mo steels in the yield-stress range of 1000 to 1350 MN/m² and the remaining ligament range of 10 to 50 mm. The use of this procedure in combination with end-on ultrasonics provides a single-specimen, single-measurement procedure for determining fracture toughness.

A second simplified J_{Ic} test procedure which can be tentatively suggested for use involves no specialized method such as ultrasonics. But it must be stated that the procedure is not as well established by the results of our laboratory. It involves using the J value at maximum load as J_{Ic}. Corten has suggested[7] that J at maximum load is a good estimate of J_{Ic} for tests in which $B/b \geq 2.0$ and $P_{max}/P_1 \geq 0.85$. (Dimensions B and b have been described in Fig. 1.) P_{max} is the maximum load from the J_{Ic} test; P_1 is the plastic-limit load for the conditions of the test and can be calculated from the expression for the plastic-limit bending moment,

$$M_1 \doteq 0.364\, Bb^2\, \sigma_{YS}. \tag{2}$$

For the tests here, the two with conditions closest to the Corten criteria are specimens 175-1 and 175-3 (see Table 2) which have B/b values of 2.00 and 1.97 and P_{max}/P_1 values of 0.65 and 0.64, respectively. For these specimens, the ratios of J_{max} to J_{Ic} are 1.26 and 1.31, respectively; in K units the ratios become 1.12 and 1.14. Based on these results and on the trend toward convergence of J_{max} and J_{Ic} with decreasing specimen size noted in Figs. 3 and 4, J_{max} appears to be a good estimate of J_{Ic} for this material and for the conditions suggested by Corten. Additional tests are underway at this laboratory to further verify the maximum load approximation for J_{Ic}.

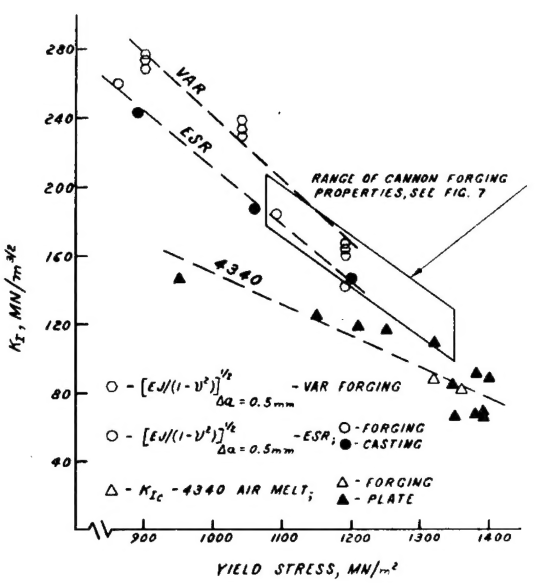

Fig. 8—Fracture toughness vs. yield stress for various steels

Conclusions

The main conclusion to be drawn here is that the $[EJ_{Ic}/1 - \nu^2]^{1/2}$ values from the steels tested provide very nearly the same measure of fracture toughness as does K_{Ic}. When J_{Ic} is calculated from the intersection of the blunting line and the crack-growth curve, $[EJ_{Ic}/1 - \nu^2]^{1/2}$ is, on average, 5 percent lower than K_{Ic}. This can be explained by considering that whereas K_{Ic} measurements correspond to a 2-percent increase in crack length, J_{Ic} measurements correspond to the very start of crack growth following crack blunting. So, as has been observed by others, the J_{Ic} procedure gives a slightly lower measure of the resistance to crack growth.

When the average value of $[EJ/1 - \nu^2]^{1/2}_{\Delta a=0.5\ mm}$, which corresponds to 1 to 4-percent increase in crack length in these tests, is compared with the average K_{Ic}, these two values agree within 1 percent. This indicates that measurement of a critical J value corresponding to a small, finite amount of crack growth is directly equivalent to a K_{Ic} measurement in the material tested here.

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